The Australian International Gravitational Observatory

by David Blair and Jesper Munch on behalf of the Australian Consortium for Gravitational Astronomy

Building a single gravitational wave detector in Australia improves all the gravitational wave detectors in the world. It improves their sensitivity and their angular resolution, their ability to probe general relativity in the strong field limit at black hole event horizons, and to probe cosmological distances.

Normally scientific instruments stand on their own merits. They have a proposed scientific program and do as well as their performance allows; if one instrument is better than another, then it can do better science. So what can be the justification for building a new scientific instrument, rather similar to others in the world and with only one new feature - it's location being Australia? A sceptic might say it has already been done elsewhere, so there is no point. Another might say if it can only increase the quantity of data…there will be nothing qualitatively new.

In the field of gravitational wave detection nothing can be further from the truth. A new gravitational wave detector in Australia improves all the other detectors in the world. In this article we will outline how this can happen, but first we will summarise the development of the field, then outline the concept for AIGO, the Australian International Gravitational Observatory, and finally discuss the enormous advances this observatory can bring to our understanding of the universe.

Gravitational Wave Research in Australia and the World

The effort to build sensitive gravitational wave detectors began with the construction of big bars of metal, first at room temperature, then cooled to cryogenic temperatures, and all equipped with vibration sensors to pick up the tiny gravitational wave strains expected from the birth of black holes according to Einstein's General Theory of Relativity.

In Western Australia during the 1990s a detector called Niobe, consisting of a 1.5 tonne bar of niobium, participated in a worldwide network of 5 detectors (called the International Gravitational Events Collaboration) that placed significant limits on the rate of black hole births in our galaxy. In those days there were hopes that the missing mass might consist of a population of black holes, some of which might coalesce creating strong gravitational wave bursts. Such events now seem to be more rare than the early experimenters had hoped.

The next step in sensitivity was to construct large scale Michelson interferometers, which could measure the gravitational wave-induced spatial strains between widely spaced mirrors. Four huge detectors were constructed at three locations in the USA and Italy. The US LIGO detectors consisted of interferometers with 4 km long arms, while the French-Italian detector VIRGO had 3 km arms. Smaller detectors were constructed in Germany and Japan. Figure 1 shows one of these detectors from the air.

After several years of development, the LIGO detectors collected one year of data at high sensitivity. This landmark improved the sensitivity to known sources by an enormous factor. The sensitivity was sufficient to detect gravitational waves originating from far beyond our own galaxy, out to a distance of almost 50 million light years, sufficient to encompass on order of 10^3 galaxies. VIRGO achieved comparable results.

By the time approvals for building the LIGO and VIRGO detectors were received, there was a good theoretical understanding of at least one type of source for which the population was relatively well known. These sources are coalescing binary neutron stars such as the famous binary pulsar system, which was used by Hulse and Taylor to prove the existence of gravitational waves (Nobel prize 1993).

Unfortunately neutron stars coalesce relatively infrequently in our galaxy…maybe once every 10^4 years. That means that 10,000 Milky Way equivalent galaxies must be within range to detect an average of one event per year. Thus LIGO had a relatively small probability (~10%) of detecting an event in one year of observation, and so it is no surprise that events have not been reported.

The above statistics were well known at the time LIGO was proposed. The initial detectors were intended to be only the

Figure 1 The VIRGO gravitational wave detector near Pisa, Italy.

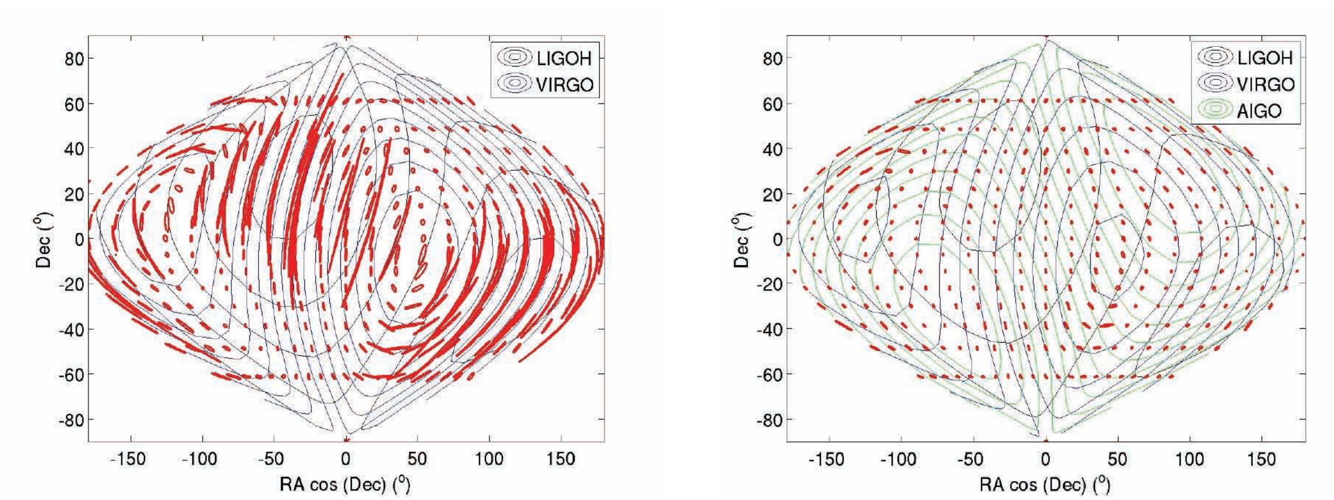
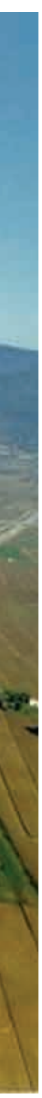


Figure 2: The angular resolution of the world array of gravitational wave detectors without and with AIGO. The ellipses represent the error box for a gravitational wave signal from each direction on the sky.



first step in a process that promised to open the gravitational wave spectrum to astronomy. They were intended to prove the technology and pave the way for a much-improved design called Advanced LIGO. VIRGO had similar development plans. The first step was essential because many scientists were sceptical that it would ever be possible to measure the very small gravitational wave strains required – strains at the 10^{-23} level corresponding to distance changes of ~10^{-19} m. The Advanced detectors have been designed to increase the sensitivity by one order of magnitude, in order to be certain of detecting signals, unless either gravitational physics was radically wrong or nature had unkindly located neutron star binaries in our galaxy alone. In either case, non-detection would be as significant as the missing neutrinos from the sun which eventually uncovered neutrino mass.

Advanced LIGO is now under construction and by 2014 should be approaching design sensitivity. Before these detectors and Advanced VIRGO come on line a run at intermediate sensitivity is planned by LIGO. In this run there is about a 50-50 chance of detecting a neutron star inspiral signal in one year of data.

Thus gravitational radiation is getting tantalisingly close to the first direct detection. The community is focussed on the imminent opening of this new spectrum for observing the secrets of the Universe and the enormous scientific opportunities it will bring.

How can one detector improve all the other detectors?
Gravitational waves are transverse waves of gravity gradient. They come in two polarisations 45 degrees apart and travel at the speed of light. With current technology they must be located flat on the earth's surface. Individual gravitational wave detectors have poor directional sensitivity – comparable to that of a single human ear. They are also susceptible to interference from electromagnetic, seismic or acoustic sources. One detector alone cannot be certain of having detected a signal because interference can be indistinguishable from a signal. The probability of interference glitches occurring accidentally in a network of detectors reduces as the power of the number of detectors. Each additional detector makes an enormous contribution, allowing the network to dig out events that otherwise cannot be separated from the noise. In addition, widely spaced detectors can use triangulation based on signal arrival times to determine the source direction. It is thus reasonable to think of the single detectors as relatively unimportant by themselves, but as essential components of a single global observatory.

Gravitational wave detectors are L-shaped to match the displacement pattern of a plane-polarised gravitational wave: when one arm of the L is stretched the other arm shrinks. The detectable part of the spectrum using ground based interferometers occurs at audio frequencies between 10 Hz and a few kHz, which correspond to signals expected from both neutron star and 1-50 solar mass black hole coalescence events. Ideally each observatory would have pairs of detectors located at 45 degrees to each other, to give sensitivity to both polarisations. However even this is not sufficient because gravitational waves are transverse waves and detectors are constrained to be flat on the earth's surface for practical reasons.

Why care about polarisation?
If you can measure both polarisations of a binary coalescence event, the signal carries with it a *complete description of the system*, including both the masses of the binary pair and the orientation of the source. When you measure both polarisations the system is so well constrained that the signal basically carries with it a message about its distance. The sources are true standard candles, or as gravitational wave physicists like to say, standard sirens. Like a siren, the frequency rises in a chirp as the coalescence proceeds. (You can hear and view such signals at the Black Hole Hunter website.)

The best way of obtaining polarisation coverage is to spread detectors around on the spherical Earth. This is fine if you have enough detectors, but if you have only two or three locations this solution could be very dangerous, because the signals can be so different from each other that you may interpret them as noise: you can lose the advantage of coincidence detection.

Thus three detectors focussed on initial confirmation of gravitational wave signals are best if they are co-aligned as well as possible. But once detection is achieved there is a strong benefit in adding another one that is able to sample the orthogonal polarisation. If the additional detector is maximally distant from the others, and if it is out of the plane, it has the added advantage of being able to combine polarisation coverage with time of flight phase delay to both locate the source on the sky and determine its distance.

Analysis of signals from an array can be undertaken coherently. Effectively we can think of detectors sampling part of an incoming wavefront, and like Very Long Baseline Radioastronomy, the combined signal is equivalent to that from an enormous telescope with angular resolution set by the spacing of the detectors. The source location can be defined to quite high precision, limited, like electromagnetic telescopes, only by the diffraction limit. Because the detectable range of wavelengths is quite large (typically a few hundred kilometres) the angular resolution is a few arc minutes.

One way to represent array sensitivity is to plot the error circles for sources uniformly distributed on the sky. Figure 2 shows the angular resolution of the current large-scale detectors, compared with how it is improved by adding a detector in Australia. The results are dramatic: the error ellipses that were tens of degrees long have turned into sub-degree sized uncertainty regions.

If you can locate gravitational wave sources to reasonable precision it becomes possible to use gravitational wave signals to direct optical and radio telescopes to image the region of the outbursts. With an Australian detector the directional resolution of the global array matches well to the field of electromagnetic telescopes.

One of the main candidates is gamma ray bursts. It is thought that some gamma ray bursts are neutron star coalescence events. The bursts that are detected from space at a rate of one every few days, appear to be strongly beamed so that only observers in the line of sight can see their direct emission. Out of the line of sight there should be a very weak afterglow that would normally be very difficult to detect. However a gravitational wave beacon can make all the difference: it allows deep electromagnetic imaging so that events can be correlated across two separate spectrums – electromagnetic and gravitational.

What can we learn from such correlated observations? First it allows a completely independent measure of the Hubble law. The luminosity distance is measured by the gravitational wave signal. The red shift is measured from electromagnetic

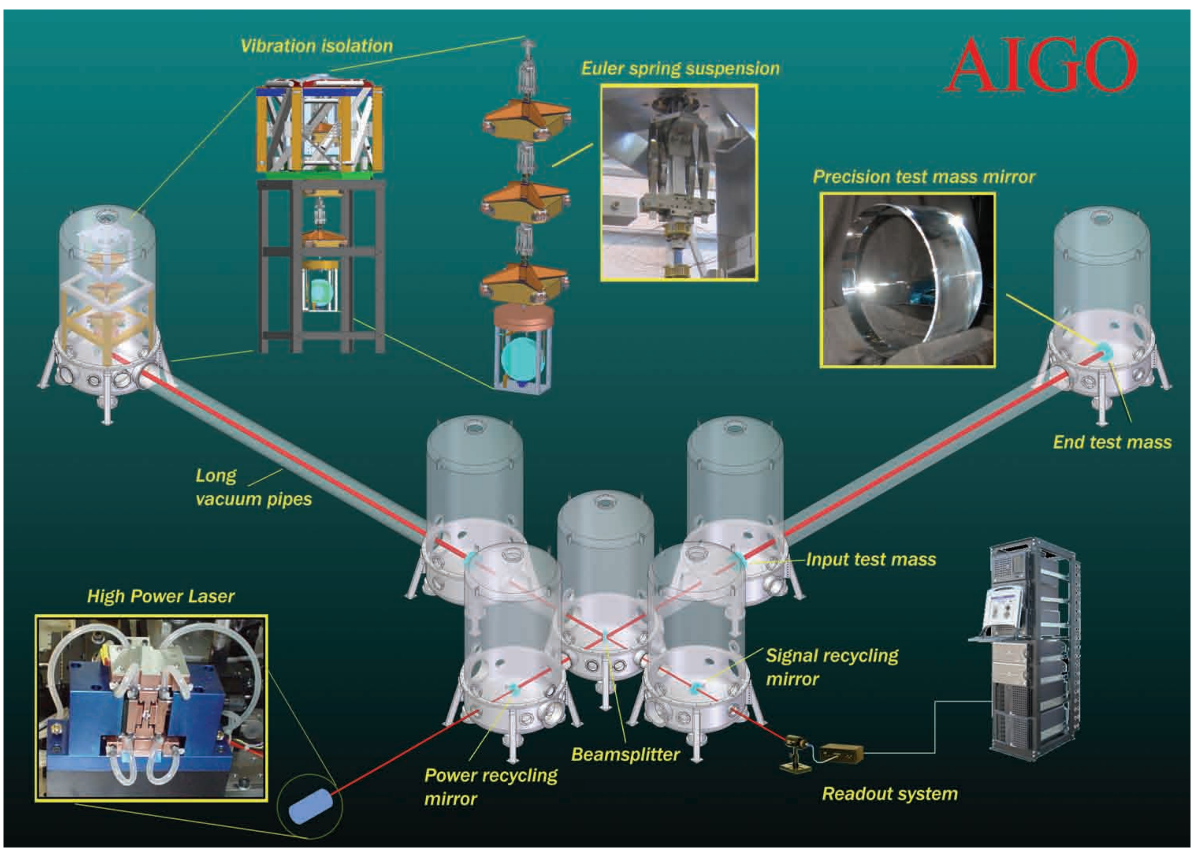


Figure 3: The design concept for AIGO. Powerful laser beams traverse two 4km vacuum arms that form a high sensitivity, high optical power Michelson interferometer. Fabry-Perot arm cavities, plus additional power and signal recycling cavities combined with high performance vibration isolation and precision low acoustic loss test masses create a system capable of detecting time varying strains in space with dimensionless amplitude ~ 10^{-24}.

observations of the afterglow, or if this is not observed, then the red shift can be measured for the host galaxy of the event. This allows direct determination of the Hubble Law and cosmic acceleration. Second, by comparing the arrival time of electromagnetic waves and photons we can make an accurate measure of the velocity of gravitational waves, which currently is only known as a theoretical prediction. Third, with gravitational waves describing the internal dynamics of the source, and electromagnetic waves describing the external structure and processes in the sources, we should finally be able to explain how these prodigious outbursts of energy occur.

The coalescence of binary black holes is another very likely source of gravitational waves. Stellar evolution theory predicts binary black hole coalescence events occurring at a rate of a few to a few hundred detectable events per year. Coalescing black holes may not have an electromagnetic signature. However because they are also standard candles, a detector array can locate them three dimensionally (angular position and distance) which in many cases can enable their host galaxies to be identified. Once this is done we can again use them for probing cosmology.

The case of black hole coalescence is one of the most exciting targets for gravitational wave detectors. This is because black hole signals allow a very clean observation of the physics of spacetime at the extremes of strong field gravity where two event horizons merge into one. These observations will constitute very deep tests of general relativity. It will be possible to test predictions of general relativity such as the black hole surface area theorem (the surface area of black holes must always increase) the no hair theorem (black holes are entirely characterised by their mass, charge and angular momentum) and the cosmic censorship conjecture (singularities must always be clothed by an event horizon).

Most of the above science is dependent on an improved gravitational wave detector array that allows accurate localisation and description of sources. The detector in Australia does this better than any other location in the world.

The Plan for AIGO

Australia currently has very strong participation in the US LIGO project. Three experimental groups and two theory and data analysis groups constitute about 50 scientists who are all actively involved.

The world community of about 1000 gravitational wave researchers is naturally enthusiastic that a detector be built in Australia. The LIGO project has offered to help Australia build a detector very similar to Advanced LIGO. The experimental research groups at ANU (Centre for Gravitational Physics), Adelaide (Laser Physics Group) and UWA (Australian International Gravitational Research Centre) have extensive expertise in key research areas, while data analysis and theory groups at Melbourne, Monash and Charles Sturt University as well as ANU and UWA contribute to the massive worldwide gravitational wave data analysis effort. The Australian Consortium for Gravitational Astronomy (ACIGA) has developed a High Optical Power Facility in Gingin, Western Australia, on a potential site for AIGO 80 km north of Perth.

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Two Australian groups (ANU and Adelaide) are supplying key components for Advanced LIGO, while the UWA group is researching aspects of high optical power technology which is the essential enabling technology to allow Advanced LIGO to achieve its planned sensitivity.

Currently ACIGA has created a roadmap and a business plan for AIGO and is working towards an international/national collaboration to build the $150M AIGO. Two advisory committees have been assisting nationally and internationally in creating the plan for AIGO. Currently the plan involves constructing a detector nearly identical to Advanced LIGO, but making use, where preferable, of Australian developed vibration isolation technology, Australian lasers and Australian optics created by the Australian Centre for Precision Optics in the CSIRO. A major part of the AIGO project will be 8 km of high vacuum pipe used for the interferometer beams. Fortunately Australia has an innovative company STM Duraduct with expertise and experience in such UHV fabrication. Figure 3 shows a concept cartoon for AIGO showing the massive vacuum system and internal components. The AIGO site has not been formally chosen yet, but the Gingin site is a strong candidate.

Thus Australian scientists are poised and ready to build this exciting international science project. We in the team believe that it "ticks all of the boxes" – jobs, industry relevance, local manufacture, boosting education and training, encouraging young people to take up science careers, international significance and international investment.

Further reading

Ground-based gravitational-wave detection: now and future: Stanley E Whitcomb 2008 *Class. Quantum Grav.* 25, 114013

Ripples on a Cosmic Sea. David Blair and Geoff McNamara 1997 Australian edition Allen and Unwin, US Edition: Addison Wesley

David Blair is Director of the Australian International Gravitational Research Centre, a WA Centre of Excellence. He has been working in the area of gravitational waves for many years, and is a member of the team proposing to build the Australian International Gravitational Observatory, AIGO. He was WA Scientist of the Year in 2007.